

Developmental Cryogenic Active Telescope Testbed (DCATT)

Responses to System Peer Review Comments

DCATT Team
December 9, 1997

Goddard Space Flight Center
Jet Propulsion Laboratory

Developmental Cryogenic Active Telescope Testbed (DCATT)
System Peer Review, September 23, 1997

Reviewer Comments/Team Responses

1. SUBSYSTEM: Optics/Stimulus
SOURCE: Unknown

SPECIFIC REQUEST: Perform Radiometric analysis.

RESPONSE: A radiometric analysis was already planned. A detailed radiometric analysis will begin as soon as the source design is finalized. (P. Davila)

2. SUBSYSTEM: All
SOURCE: Dave Redding, JPL, (818) 354-3696

SPECIFIC REQUEST: Develop a strawman experimental plan for PDR.

SUPPORTING RATIONALE: 1) It will help in defining hardware buildup sequence.
2) Experiments are as much of a product as the hardware.

RESPONSE: This will be done. (C. LeBoeuf)

3. SUBSYSTEM: Fast Steering Mirror / guide
SOURCE: Dave Redding, JPL, (818) 354-3696

SPECIFIC REQUEST: Need to identify how the source will be jittered.

RESPONSE: We will keep it in mind as we design the stimulus. Feel free to suggest ways of doing it. (A. Lowman)

4. SUBSYSTEM: Dispersed Fringe Sensor (DFS)
SOURCE: Bill Hayden, GSFC, Code 721, (301) 286-8963

SPECIFIC REQUEST: Need to understand the need for a segment masking mechanism, and a trade with other phasing techniques. Note that the DFS already requires a mechanism for the grism.

RESPONSE: When we analyze/model the DFS, we will look into whether it is practical (or even desirable) to sequentially phase the segments without masking or moving previously-aligned segments. If segment masking is needed in DCATT, a simple mask near the DM would suffice. The current baseline for NGST is to move each segment out of the way after it is aligned and then back to the same position.

This will place stringent requirements on the accuracy of the actuator encoders, so eliminating the need to move or mask segments would be ideal. (A. Lowman)

5. SUBSYSTEM: Primary mirror fabrication
SOURCE: Bill Hayden, GSFC, Code 721, (301) 286-8963

SPECIFIC REQUEST: On nickel plating, keep in mind

- bi-metallic bending due to:
 - hot bath (>190 degrees F)
 - heat developed during turning & polishing
- Thinner plating has a reduced effect

RESPONSE: These effects are understood and we are aware of them. Currently we have an effort to analyze and specifically quantify each effect and what it means in terms of figure error and hopefully system performance. The diamond turning and polishing people require a certain amount of thickness to work with (.005 to .006 inch). Our analysis will show whether the amount of error introduced by the nickel plating can be taken out during the diamond turning/polishing process. (A. Morell)

6. SUBSYSTEM: Fast Steering Mirror (FSM)
SOURCE: Bill Hayden, GSFC, Code 721, (301) 286-8963

SPECIFIC REQUEST: FSM requirements/specifications need to start with a measurement of the disturbance environment. To validate NGST, the starting point would be the expected NGST environment (which may be different than the DCATT environment)

RESPONSE: The initial DCATT system (without the FSM) will be supported on vibration isolation. In this mode, there should be little vibration input of a nature that the FSM would be capable of eliminating. Once the FSM is phased in, there are two potential modes under which the system could be tested. One involves removing the vibration isolation (i.e. lowering the table onto the hard supports) and seeing whether the FSM can remove the laboratory environment vibrations. To investigate this requirement, the vibration environment in the proposed facility (CIA room in building 7) shall be characterized shortly to give an early indication of the environment. It will also be recharacterized once the system is built. The other mode would involve injecting specific vibration modes into the system. This will be based in part on the expected NGST environment (e.g. momentum wheel modes, etcetera). In order to develop these requirements for the DCATT system, a plan must first be put together on what vibration modes (NSGT or other) should be investigated and how it is planned to implement them. DCATT will need input for this from the NGST Systems Engineering group. The DCATT team will continue to work this area. (C. LeBoeuf)

7. SUBSYSTEM: Mechanical

SOURCE: George Voellmer, GSFC, Code 723, (301) 286-8182

SPECIFIC REQUEST: The concepts presented for the mirror actuation and the mechanical structure were too preliminary to give a good review. My thoughts on what I saw:

- a) If thermal gradients are expected to be a problem, it needs to be addressed in the bench as well as in the telescope structure.
- b) The springiness of the proposed primary mirror mounting flexures, coupled with the mass of the segments, is going to give a lot of low frequency piston and side-to-side jiggling. I suggest a flexure system that is more kinematic and stiffer.
- c) A lightweighted AC flat should be investigated. A heavy flat up on that stand is going to make you miserable every time you want to use it. You'll need a crane to lift it, huge mounting hardware, and a very beefy stand.

RESPONSE:

- a) Agreed. We are only now beginning our thermal analysis and mechanical structure design. The entire structure will be reviewed and analyzed to ensure that we will meet our metering requirements in all axes. (C. LeBoeuf)
- b) The design presented at the review used three actuators and three flexures as the actuators/mirror interface. The baselined flexures only release two degrees of freedom (moments), this means that all translations and one rotation are constrained, therefore three of these flexures working together on each segment allowed for a relatively stiff assembly. (A. Morell)
- c) A lightweighted flat will be investigated thoroughly. There are various considerations which must be made however, including cost, schedule, and the fact that we were hoping to use the same flat we get for the ambient test for the future cryogenic testing. A polished Zerodur flat of the right size has been discovered and is presently being procured (at a very good price and available immediately). We are currently investigating the best way to support it. The GSFC optics group has some experience with large flats and this will be drawn upon in the mounting studies as well as experience from outside optics groups such as HDOS and KODAK, whenever possible. The CIA facility does have an overhead crane. (C. LeBoeuf)

8. SUBSYSTEM: Various

SOURCE: Sandy Montgomery, MSFC, (205) 544-1767

SPECIFIC REQUEST:

- a) Add to package a viewgraph of NGST configurations.
- b) After integration but prior to alignment of DCATT components, perform modal survey.
- c) Show location of Deformable Mirror, Fast Steering Mirror, Wavefront Sensor, and Stimulus driver electronics, as well as displays, PC s, keyboards, etcetera. Plan out telemetry system for testbed.
- d) Consider using anti-reflective coatings for bench optics.
- e) Need to design optical interface between the seven primary mirror segments in the collimated beam and the Shack-Hartmann 60 lenslet array.
- f) Indicate which steps in the primary fabrication, test, and alignment plan are MSFC responsibilities.
- g) Eliminate the Dispersed Fringe Sensor.
- h) There are too many optical elements.

SUPPORTING RATIONALE:

- a) It will make the package accessible to a wider audience.
- b) This is necessary for jitter compensation in the controller design. You do not want to do this after alignment since the instrumentation (accelerometers, cables, etcetera) are intrusive and removal will disturb precisely positioned elements.
- c) This stuff will take up a lot of room. Routing cable bundles can be tricky. Electronics are heat sources - keep away from beam path. When closing the loop there will be anomalies that will cause a search for EMI and ground loops.
- d) Secondary reflections are a noise source.
- e) This will avoid confusion and increase sensitivity of tracking the centroid spot from each segment. It will also assure direct mapping from incident light to actuator commands.
- f) This will avoid redundancy and strengthen accountability.
- g) The basic function of coarse alignment can be accomplished by developing a search and scan function to drive the segment actuators. This automates initial calibration and saves effort (this is what was done in PAMELA).
- h) Too many redundant DM s, beamsplitters, fold mirrors. All are potential error sources. Start with simplicity, work towards greater functionality later.

RESPONSE:

- a) Will do. (C. LeBoeuf)
- b) Good input. Sounds like a very good idea. We will plan to implement. (C. LeBoeuf)

c) Good input. We have only recently completed a comprehensive list of all of the components which will need drive electronics as well as the final optical layout on the bench. The next step will be to start laying out the locations of wiring and electronics on and around the optical bench. Vibration isolation and EMI suppression will be kept in mind during the layout and design of support hardware. (C. LeBoeuf)

d) Absolutely! We have already considered an AR coating for the vacuum window on the camera head. The only other refractive surfaces in the system are on the beamsplitter and any compensating elements. Since we have broken the interferometer out of the stimulus and into a separate wavefront sensor, the beamsplitter is now located near the telescope focus and we can dispense with the compensating elements. The back surface of the beamsplitter will be AR coated. (A. Lowman)

e) The design of custom lenslet arrays will be pursued to be used in testing with the Shack-Hartmann wavefront sensor which GSFC has already procured. AOA has indicated that they will work closely with us to do this. Also, the procurement from them included programming time to make changes in the delivered scripts and software to accommodate DCATT pupil geometries. (P. Davila)

f) We currently have a draft version of a letter of agreement with MSFC, specifying the responsibilities of the various organizations which will be involved in the fabrication and characterization of the primary mirror. After the polishing of the mirror, final characterization, integration, and alignment will be solely the responsibility of GSFC. (C. LeBoeuf)

g) Search and scan is already part of the operation sequence. Yes, this is somewhat redundant with the DFS. The DFS has the advantage of large dynamic range and immediate readout of the piston; you don't have to hunt to get resolvable interference fringes. One of the purposes of DCATT is to study methods of phasing a segmented telescope, so we can use it to explore different phasing techniques. (A. Lowman)

The DFS will continue to be baselined as the method of coarse wavefront sensing. Other groups, both within the government and within industry, are encouraged to develop alternate breadboard wavefront sensing hardware which can be tested in DCATT. The Shack-Hartmann hardware which GSFC has procured will also be further developed as DCATT evolves. (P. Davila)

h) I agree that we should try to simplify the system, and we have already addressed that since the review by breaking the stimulus into three pieces: a source module; a telescope simulator (aberration generator); and an interferometric wavefront sensor (IWFS). The source module will be built first, followed shortly by the telescope simulator; the IWFS is purely for diagnostic purposes and need not be ready when DCATT first becomes operational. There really are not any redundant elements, even in the original stimulus/system design. The DM in the stimulus will be used to

generate random aberrations that cannot be had with the telescope. This DM is a freebie that JPL no longer uses, so the cost of adding it is minimal. In our most recent design, the DM is only in the beam path when we are using it to generate aberrations, so it will not degrade the wavefront in normal operation. There are no redundant beamsplitters either; in the layout presented at the peer review, one was part of the interferometer (which as an IWFS is now completely out of the beam path used for illuminating the system); the other is essential for getting the light into the system. The design that showed three plates only contains one beamsplitter; the other plates were needed for correcting the aberrations of a tilted plate (the beamsplitter). These compensators are not needed in the present design, which has the beamsplitter near the telescope focus since we no longer need to illuminate from the back. This simplified design also reduces the number of mirrors in the beam path, while simplifying alignment of the source and telescope simulator to the system. (A. Lowman)

9. SUBSYSTEM: Mechanical Structure / Autocollimating Flat
SOURCE: H. John Wood, GSFC, Code 717, (301) 286-8278

SPECIFIC REQUEST: The 40 inch autocollimating flat should be supported by vacuum.

SUPPORTING RATIONALE: The 40 inch secondaries on KPNO Mayall telescope and the 4 meter Blanco telescope at CTIO in Chile are both supported by vacuum systems. I will attempt to get drawings of these systems for you.

RESPONSE: Thanks John. We would appreciate that. (C. LeBoeuf)

10. SUBSYSTEM: All
SOURCE: Chris Burrows, STSCI

SPECIFIC REQUEST: Need overall system stability at well below the wavefront specification or periods between the wavefront sensing updates. Look at

- Temperature effects on aluminum mirrors
- Deformable Mirror long term stability when actuated

RESPONSE: We will be starting a thermal analysis of the system within the next couple of weeks. The overall stability issue is one of the areas that the testbed is being built to address/study. The stability of the deformable mirror will be characterized once it is delivered. (C. LeBoeuf, P. Davila)

11. SUBSYSTEM: Requirements
SOURCE: Linda Pacini, GSFC, Code 701, (301) 286-4685

SPECIFIC REQUEST: Your requirements for the optical design are not really requirements but derived design parameters. You should document the requirements flowdown and decisions made (e.g. why hex? why 633nm? etcetera).

RESPONSE: Presenting a requirements flowdown will be a goal for the next Quarterly Review of DCATT. (C. LeBoeuf, P. Davila)

12. SUBSYSTEM: Mechanical Structure
SOURCE: Jeff Bolognese, GSFC, Code 721, (301) 286-4252

SPECIFIC REQUEST: Will a mapping of nickel thickness over the surfaces of the mirror segments be developed and applied to the mirror FEM?

SUPPORTING RATIONALE: Variations in nickel thickness will affect the thermal distortion of the mirror segments.

RESPONSE: Currently the plan is to model only a uniform thickness on nickel and check the results. The current segment design is expected to meet optical specifications at room temperature only. Therefore differences in nickel thickness as a result of the plating or machining operations are not as important provided the correct figure is achieved. Also, based on the experience of our plating shop, we expect an adequately uniform thickness of nickel. (A. Morell)

13. SUBSYSTEM: Mechanical Structure

SOURCE: Jeff Bolognese, GSFC, Code 721, (301) 286-4252

SPECIFIC REQUEST: More realistic values are needed for the mirror diamond turning accelerations. If it will be done at variable speeds, this should be modeled. Also, it may be necessary to model the entire mirror assembly, as turned, to correctly represent stiffnesses and boundary conditions during turning. If distortions are still severe, perhaps different ways of constraining the mirrors should be investigated.

SUPPORTING RATIONALE: The loads and distortions that are predicted to occur during the diamond turning of the mirror seem to be driving mirror distortion budgets. It needs to be verified if they are really that severe, and if so, ways should be investigated to minimize distortions.

RESPONSE: This request is being addressed. The mirror mounting scheme has been modified and the method of modeling the loads has been corrected to represent the actual nature of the load and the possible range of turning speeds. A better model of the mirror segment, including the new mount design is being developed. When a reasonably mature design for the turning fixture is agreed upon it will be modeled and the new mirror model integrated with it. A conservative model of the new mount scheme indicates that the manufacturing-induced displacements are acceptable. (M. McGinnis)

Also, the diamond turning operation at Oak Ridge National Laboratory includes an error mapping and correction for repeatable errors which historically has been able to eliminate about 80% of the repeatable error. (C. LeBoeuf)

14. SUBSYSTEM: Mechanical Structure

SOURCE: Jeff Bolognese, GSFC, Code 721, (301) 286-4252

SPECIFIC REQUEST: More analysis and design work is necessary for the DCATT structure. Preliminary distortion analyses (thermal and other) should be performed to help determine realistic design and material choices.

SUPPORTING RATIONALE: Although the DCATT structure is still in its early stages, plans should be made to analyze structural concepts before deciding on the use of composites versus metals. It would be particularly important to examine loads and distortion due to thermal expansion mismatches.

RESPONSE: More work is planned in this area. Work is underway to characterize the thermal and humidity environment we will be operating in. The entire DCATT layout has been received by 721 in IGES format so that the information needed for a STOP analysis can be extracted. (M. McGinnis)

15. SUBSYSTEM: Dispersed Fringe Sensor
SOURCE: John Hagopian, GSFC, Optical Test Section, (301) 286-3524

SPECIFIC REQUEST: DFS dynamic range of 187 microns of piston was quoted. Does this dynamic range include losses due to other aberrations and some level of jitter? If not, then a detailed error budget for deployment tolerances and allowable jitter should be developed and folded in to determine a realistic dynamic range.

RESPONSE: No, this is for pure piston, done in a back-of-the-envelope calculation. It does not even include the diffraction spot size, which will reduce this number by at least a factor of 2 or 3. As per suggestions from you and other reviewers, we intend to do a much more detailed analysis and simulations to include the effects of tilt, aberrations, and jitter. (A. Lowman)

16. SUBSYSTEM: DCATT Source Flat
SOURCE: John Hagopian, GSFC, Optical Test Section, (301) 286-3524

SPECIFIC REQUEST: I strongly recommend that DCATT procure a lightweighted aluminum flat at all costs. This may be one of the most important things that can be done to ensure DCATT's success. If this is not possible it may be necessary to reconsider a horizontal telescope configuration.

SUPPORTING RATIONALE: The baselined DCATT autocollimation flat weighs between 400 and 800 lbs and will be suspended approximately 10 feet above the AO bench. This is probably the worst element in the current design. A seven inch thick glass mirror will distort significantly when oriented in this configuration. Building a mount to reduce this distortion will be very difficult. Every attachment point or contact region will induce distortion in the mirror which may be significantly different during the test and integration. In fact, it will be extremely difficult to test the flat in its present configuration. In addition, any vibration dampening system will have more difficulty responding to this type of configuration. If active vibration control is required this may make the task of developing a closed loop system impossible.

RESPONSE: A lightweighted flat will be investigated if necessary. There are considerations which must be made however, including cost, schedule, and the fact that we plan to use the ambient test flat for the future cryogenic testing. A polished Zerodur flat of the right size was discovered and procured (at a very good price and available immediately). The best way to support it is currently being investigated. The GSFC optics group has some experience with large flats and this will be drawn upon in the mounting studies as well as experience from outside optics groups such as HDOS. A rough calculation using a nine point Hindle mount showed that gravity sag could be reduced to an acceptable level. A much more thorough investigation and analysis is still necessary. If it is absolutely necessary to fabricate an aluminum flat for the ambient portion of the test then this will be done. However, it is desired to fully investigate the possibility of using the Zerodur flat. Any suggestions you can offer to that end would be very welcome. (C. LeBoeuf, P. Davila)

17. SUBSYSTEM: Telescope

SOURCE: John Hagopian, GSFC, Optical Test Section, (301) 286-3524

SPECIFIC REQUEST: The mounting ring should be machined into the segments to preserve some semblance of cryo capability. Our experience with the CIRS optics has shown that aluminum mirrors fabricated under the controls baselined for DCATT can perform well at cryogenic temperature. The radius of curvature will change, but it is possible that modifications can be made to compensate. Therefore I strongly recommend that all telescope and flat mirrors be fabricated with cryo capability in mind, and that bonded interfaces be eliminated or designed accordingly.

SUPPORTING RATIONALE: The current baseline of DCATT does not utilize the C for Cryogenic. There are however, many reasons for maintaining a cryogenic capability for future testing. The current design calls for epoxying a circular, ribbed, mount on the mirror segments for attaching the actuators. This design would probably preclude cooling the segments.

During CIRS testing we were required to have cold adjustment capability, we were unable to find motors and translators which worked at 170 K. We were able to use heaters to maintain our motors at elevated temperature and thermally isolate them from our hardware by using thermal isolators, MLI and cold shields. It is very possible that the same can be done with DCATT mirror actuators. Therefore a cryogenic compatible philosophy could give extra capability without compromising cost and schedule for the current objective of D C ATT.

RESPONSE: All bonded interfaces have been eliminated and the segment pedestal/interface surfaces is an integral part of the mirror segment. (A. Morell)

18. SUBSYSTEM: Systems Engineering

SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: Some possible additions to consider for your DCATT Team Organization chart include system engineering, thermal engineering, cryogenic engineering, contamination, detectors, safety, flight assurance, software, quality assurance, and system level integration and test. Science could use a representative to focus on requirements. The goal would be to assure that even for the ambient demonstration system that the design proceeds in a way that can most easily adapt to a cryocapable system. The final goal would be to provide as much useful information as possible for the next generation space telescope.

RESPONSE: I agree to some degree and I appreciate your thoroughness. In this case, DCATT has no flight aspect. The only detectors involved, at least at first, are commercially available CCD cameras. We do intend on getting some expert advise on how to model them in our integrated models. The cryogenic planning aspect will be phased in after the ambient testbed development is at cruising speed. We do now have thermal engineering and software development support which I will add to my chart. We have NGST project support as well as solicited advise from wavefront sensing and control experts to focus on requirements, and I think our top level requirements at least are close to being squared away. Safety, contamination, and quality assurance will definitely be involved, but not necessarily have specific people dedicated to DCATT. Systems engineering support is highly utilized at the center and hard to come by. We will hopefully be getting an increased level of support in this area from the NGST project as their manpower levels increase. (C. LeBoeuf)

19. SUBSYSTEM: Mirror mechanical design
SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: I recommend looking into 6 degrees of freedom on the primary mirror.

SUPPORTING RATIONALE: To begin with, this would allow an automated setup of the mirror. If there is any chance that for the next generation space telescope that a 6 degrees of freedom primary mirror could significantly improve performance, then this would be a second reason to consider trying this out with the testbed.

RESPONSE: A six DOF system is now the DCATT baseline. The current baseline utilizes a hexapod (Stewart platform) design. (A. Morell)

20. SUBSYSTEM: Modeling
SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: The scaling of a 1 meter system to an 8 meter system needs to be looked at carefully.

RESPONSE: An important distinction must be made between the testbed as a functional, system demonstration and the testbed as designed hardware. I have restated the objectives of DCATT to more accurately express our intent:

1. Test in hardware a system having the functional elements of NGST and validate models which can be scaled to predict NGST performance.
2. Explore wavefront sensing/control techniques and algorithms and their ability to reduce large wavefront errors to diffraction limited values. (In other words, study the robustness of different methodologies and find the envelope of controllability.)
3. In support of higher objectives and NGST, become expert with active optical technology through hands-on experience.

It is not the intent of DCATT (at least not in Phase 1 or 2) to build a scaled down hardware version of NGST. We have studied details of the NGST yardstick in order to design to scales which we feel can adequately represent the functions of a future NGST without introducing all of the testing difficulties of a very large primary. The hardware results of DCATT will be used to compare to an integrated model of the DCATT system. This comparison will be used to validate/improve the integrated modeling tools and methods, especially in the area of wavefront control modeling. As the modeling tools are used to predict real NGST behavior, the issues of scale will certainly be thought about and addressed, but the scaling connection will be done entirely in modeling, not in hardware. (C. LeBoeuf)

21. SUBSYSTEM: Telescope

SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: You may want to consider whether you want to have a mirror coating over the nickel.

RESPONSE: Other types of coatings, such as gold or perhaps an aluminum overcoat over the nickel, have been considered.

Below is some typical reflectance data at representative wavelengths. Although not shown, aluminum reflectance at 2 microns is lower than that of nickel according to John Osantowski. The planned approach for now is to hold off on the decision until the radiometric analysis has been completed. Now that the design of the Stimulus has been simplified and the number of optical elements reduced, it is hoped that there will be adequate signal/noise at all measurement wavelengths with nickel coatings. A requirement is needed from the modeling team on a minimum acceptable signal/noise for a minimum integration time at a couple of different wavebands. Also needed is a requirement for maximum acceptable signal level to avoid damaging the cameras. (P. Davila)

Gold:	563.5 nm	88% reflectance
	620 nm	95% reflectance
	2.0 microns	99.4% reflectance
Electroless Nickel:	620 nm	58% reflectance
	2.0 microns	76% reflectance

22. SUBSYSTEM: Error Budget

SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: It is important to complete the flow down error budgets to the various subsystems as soon as possible. It may be necessary to tighten some flowdown requirements in order to loosen others. I also recommend updating the optical performance allocation charts, as needed.

RESPONSE: The team is presently in the process of doing this. (E. Young)

23. SUBSYSTEM: Thermal

SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: There may be some trades concerning the degree of temperature control needed and the design details.

RESPONSE: More work is planned in this area. Work is underway to characterize the thermal and humidity environment we will be operating in. The entire DCATT layout has been received by 721 in IGES format so that the information needed for a STOP analysis can be extracted. (M. McGinnis)

We also now have thermal support from Code 724 and they will begin more detailed thermal analysis shortly. (C. LeBoeuf)

24. SUBSYSTEM: All
SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: I concur with using commercial off the shelf hardware and software, where possible.

25. SUBSYSTEM: Schedule
SOURCE: Mike Roberto, GSFC, Code 704, (301) 286-4004

SPECIFIC REQUEST: With some of the hardware and testing being provided by outside sources, the control of interfaces, schedules, etc. will need careful attention.

Finally, I believe you have a very ambitious schedule.

RESPONSE: Yes, we realize the schedule we are pushing for is challenging. However, I believe it to be attainable, given the agreements between centers which are already in place, the fact that we have solicited early participation of everyone who will be involved in the processes, and the commitment and talent of the people involved. The NGST project needs the information from DCATT to assist in decision making in pre and early phase A. The DCATT team will continue to push the schedule and deliver an operational system as soon as is possible. (C. LeBoeuf)

26. SUBSYSTEM: Radiometric performance
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: Radiometric performance was not considered. It is well known that any phase retrieval method will be a strong function of SNR and thus one would like to bracket the range under which NGST will operate. Naively one could say that we could just "turn down" the source brightness or shorten the detector integration time and this may be true. However these issues have not been addressed.

RESPONSE: The radiometric performance analysis has been started and will be completed once a source design is finalized. (E. Young)

27. SUBSYSTEM: Performance comparison with NGST
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: Although the ultimate goal is to achieve diffraction limited performance at 2 microns, how will the wavefront dynamic range and spatial frequency structure compare with what can be expected for NGST ? or is this knowable at this time ?

RESPONSE: This is a difficult question to answer at this time. The NGST wavefront dynamic range and spatial frequency structure will be highly configuration and material dependent. For Phase 1 DCATT development, the configuration and materials will be vastly different from those being independently pursued by the mirror demonstration contractors. However, it is hoped that DCATT will help identify generic system level problems common to both NGST and DCATT. (P. Davila)

28. SUBSYSTEM: Dispersed Fringe Sensor
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: Although I believe the Dispersed Fringe Sensor (DFS) to be a robust form of interferometry for coarse alignment, the effects of low and mid-spatial frequency structure on each of the individual segments needs to be quantified in more detail and how these will affect the overall coarse and fine alignments. I believe these effects will turn out to be relatively minor, however they have not been addressed in a quantitative sense.

RESPONSE: Good idea. We will include mid-spatial frequency errors in our DFS analysis/simulations in addition to the low-frequency errors (aberrations) other reviewers also suggested. We need to consider the effects of mid-spatial frequencies on the phase retrieval measurements as well. (A. Lowman)

29. SUBSYSTEM: Phase Retrieval
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: The actual phase retrieval process at this time is definitely an open issue. There are a multitude of phase retrieval methods currently available and each of these (or a limited subset) should be systematically addressed and quantitative assessments of their respective accuracies and precisions with respect to sampling, jitter, noise, finite pixel size, finite spectral bandpass, defocus range, corrupted pixels, detector effects and robustness needs to be made before any one method should be chosen. Also these methods should be directly compared to interferometric methods and to Shack-Hartmann.

RESPONSE: We will pursue this through an independent analytical study to compare different methods of wavefront sensing. This study will be directed through DCATT and the results will be used to plan future DCATT activities. (P. Davila)

30. SUBSYSTEM: Phase Retrieval
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: A related issued to numbers (28) and (29) above is that of the effect of wavefront aliasing in the entire alignment (coarse and fine) process, i.e. spatial frequency components will appear in the wavefront that are beyond the detectable range due to spatial bandwidth limitations inherent in the phase retrieval process. These components will "alias" into the lower frequency terms creating errors. Note that this effect can be modeled as part of the phase retrieval modeling process.

RESPONSE: We will keep this in mind. (P. Davila)

31. SUBSYSTEM: Telescope fabrication
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: Will there be any "print through" from the diamond turning process? If so how much in terms of amplitudes and periods on the mirror surfaces. This could adversely effect the phase retrieval process.

RESPONSE: The thickness of the face sheet has been calculated using existing formulas/relationships between the facesheet thickness and the pocket size. Current thickness of 3mm meets all the established criteria for avoiding print through. There should be no print through on our segments.(M. McGinnis, A. Morell)

32. SUBSYSTEM: Phase Retrieval
SOURCE: Rick Lyon, CESDIS/UMBC, GSFC Code 930.5, (301) 286-4302

SPECIFIC REQUEST: Some methods of phase retrieval work well with an extended source and thus an extended source should be able to be introduced into the stimulus.

RESPONSE: Sounds like something we should consider. At the very least, we'll make sure there's room to get another fold mirror in the beam, for feeding an extended source or other alternative sources into the system. (A. Lowman)

33. SUBSYSTEM: Infrared Testing
SOURCE: John Osantowski, GSFC Code 717, (301) 286-3873

SPECIFIC REQUEST: The discussion on how you demonstrate to the outside community that DCATT works and shows us a viable technical path to the NGST deserves much more thought. Tests in the visible will not demonstrate diffraction limited imaging at 2 microns.

SUPPORTING RATIONALE: Sure you can take the wavefront data and show diffraction limited performance at 2 microns by analysis, but this is not the headline stuff that will keep NASA advisory panels awake. The idea of a 2 micron image test that shows DCATT locking into a diffraction limited mode and staying there for extended periods under the influence of external perturbations is convincing.

RESPONSE: We think this is an excellent idea. The only refractive elements in the system are the beamsplitter and its compensating optics; their effect on the wavefront at 2 μ m is just a focus shift. The only real complication is the need for custom coatings on these elements, or a second beamsplitter/compensator for use at 2 μ m. I consulted a coatings expert, and he thinks the coatings are feasible and can be done at a reasonable cost --- maybe \$5-7K at a commercial shop. Possibly much less if the custom coatings are done in-house at GSFC. It will mean buying an IR source and an IR camera, which may be expensive. We are presently looking into our options. (A. Lowman)

34. SUBSYSTEM: Systems
SOURCE: John Osantowski, GSFC Code 717, (301) 286-3873

SPECIFIC REQUEST: How about a chart that graphically shows what elements of NGST DCATT is designed to validate.

RESPONSE: Such a chart is in existence. Attached is a copy. (C. LeBoeuf)

35. SUBSYSTEM: Stimulus/WFS
SOURCE: John Osantowski, GSFC Code 717, (301) 286-3873

SPECIFIC REQUEST: I recommend that you work out a plan for testing DCATT in the event that the Stimulus/WFS subsystems are not ready on schedule, since it may impact your design choices now.

SUPPORTING RATIONALE: The Stimulus/WFS subsystem, in total, is as big as the rest of DCATT in my view. So what happens if development of this subsystem gets into trouble? What is the team's plan to proceed with validation and demonstration of the applicable technology until the Stimulus/WFS is ready? What are your options if it's never ready?

RESPONSE: The WFS is a separate entity comprised of an already selected off-the-shelf CCD camera and a dispersed fringe sensor and I do not foresee any obstacles to having this device ready on schedule. The dispersed fringe sensor will be one of the first items we design/analyze/procure. We have reviewed the schedule and the complexity of the Stimulus and have decided to break it into three less complex systems, one containing the source, and lasers (Stimulus), one containing the aberration generation elements (telescope simulator, TS), and the third the interferometer (now called the interferometric wavefront sensor (IWFS)). The source will have top priority schedule-wise, followed by the TS and lastly the IWFS, which is used to score the performance of other WFS's but is not necessary when DCATT first starts operation. The new design is also simpler and does not have nearly the same difficulties concerning the beamsplitter design that the original layout did. The other issue that the new design addresses is a technical one, basically the concern of double passing the light through the AO bench. The new design allows the source (from the Stimulus) to be placed at the telescope focus and the IWFS to be placed at the back end of the AO bench train. Therefore, the light is double passed through the telescope only and single passed through the optic bench to the phase retrieval wavefront sensor (WFS) and the IWFS. Another benefit to this is having a stand alone interferometric wavefront sensor which can be used not just to score the final wavefront but also later as the primary wavefront control technique, as this is a method which NGST would like to investigate. I am confident that the new Stimulus will be available on schedule. If for some reason the illumination module isn't delivered on time, the system could be operated with a white light source, a couple of lenses and/or microscope objectives, a pinhole, and some filters. While we have been and are putting some thought into contingency plans, we cannot afford to get too deeply into contingency planning without seriously impacting the schedule we are trying to meet. (C. LeBoeuf)

We will procure sources that can be used independently of the Stimulus/WFS. For example, if a tungsten halogen bulb is baselined as one of the Stimulus sources, we will buy an extra and have in-house at GSFC to use as a source of our own while waiting for the delivery of the Stimulus. Wherever feasible from the point of view of schedule and budget we will purchase multiple sets of components. We are planning to buy two identical CCD cameras for phase retrieval, one to be integrated into JPL's wavefront sensor and one to be kept and used at GSFC in the interim and as a spare after delivery of the JPL WFS. (P. Davila)

36. SUBSYSTEM: Telescope Fabrication
SOURCE: John Osantowski, GSFC Code 717, (301) 286-3873

SPECIFIC REQUEST: After diamond turning the aluminum mirror assembly at Oak Ridge, there is reference to an error mapping and correction step. Is there a second cut on the mirror assembly after this? Please clarify.

RESPONSE: The error mapping will be used to do additional diamond turn cuts to correct for repeatable errors. (C. LeBoeuf)

37. SUBSYSTEM: Telescope Fabrication - Optical Testing
SOURCE: John Osantowski, GSFC Code 717, (301) 286-3873

SPECIFIC REQUEST: I strongly recommend that the interferometric test with the null lens be repeated after the second diamond turning prior to the polishing step. This can be done at Oak Ridge, GSFC, or University of Arizona.

SUPPORTING RATIONALE: The current plan calls for the mirror assembly to go directly to the University of Arizona after the nickel is diamond turned. I suspect that traceability before and after turning is something you will wish you had done if there is a problem after the mirror is handed off to Arizona.

RESPONSE: We are planning to perform the interferometric test with the null lens after the second diamond turning and prior to the final polishing. The test will be done at University of Arizona. (P. Davila)

38. SUBSYSTEM: Telescope Fabrication - Nickel Plating
SOURCE: John Osantowski, GSFC Code 717, (301) 286-3873

SPECIFIC REQUEST: If the diamond turning process is able to generate the required mirror figure, which you should know after the interferometric null lens tests, the University of Arizona should focus on improving mid-frequency and microroughness and limit the amount of figure error correction. This philosophy is then consistent with a .002 to .003 inch thickness of nickel.

RESPONSE: The diamond turning process is not able to generate the required mirror figure, which is $\lambda/5$ RMS wavefront error at 633 nm (or $\lambda/10$ RMS surface error) with less than 80 Angstroms of surface roughness in the 2 to 200 micron spatial frequency domain. During our last teleconference with MSFC/ORNL/UoA on September 30, 1997, Marty Valente from the University of Arizona stated that in order to go from the 1 wave RMS figure, 200 Angstroms RMS surface roughness mirror delivered to them to the 0.1 wave RMS figure, 80 Angstrom RMS surface roughness mirror that we need, they need about .003 inch of nickel remaining after the second diamond turning, which implies a total plated nickel thickness of .005 to .006 inch. This thickness was agreed upon by all parties involved. (P. Davila)

39. SUBSYSTEM: General
SOURCE: Pete Maymon, GSFC Code 717, (301) 286-8937

SPECIFIC REQUEST: I feel the bullets on your initial viewgraphs on DCATT Objectives and Goals need to be reprioritized in the order of importance. There was too much emphasis on the telescope. I felt the consensus from the review is that first and foremost that DCATT is a system demonstration breadboard which will validate your integrated modeling tools and understanding of your error budgets.

RESPONSE: I have refined the objectives based on input received from the review and the NGST project. The new ones are shown in response to comment number 20. I do not think the goals listed at the peer review are that far off but I will review them. Perhaps they are not complete enough. (C. LeBoeuf)

40. SUBSYSTEM: General
SOURCE: Pete Maymon, GSFC Code 717, (301) 286-8937

SPECIFIC REQUEST: The optics design, analysis, modeling team seemed to be working together well. However, during the review, there appeared to be some disconnects with the optics alignment and test engineers (For example, the discussion on the telescope fabrication, alignment, and test plan). Recommend improving teaming and communication with them.

RESPONSE: The team will focus on improving communication with all of the optics group members. (P. Davila)

41. SUBSYSTEM: General
SOURCE: Pete Maymon, GSFC Code 717, (301) 286-8937

SPECIFIC REQUEST: I am concerned about the interfaces between JPL and GSFC. There needs to be Interface Control Documents (ICD) generated. These ICDs do not need to be as formal as typical flight project ICDs. However, they need to be detailed enough so JPL and GSFC come together properly in the end.

RESPONSE: Agreed. We are currently working on a requirements and interface control document. (C. LeBoeuf, P. Davila)

42. SUBSYSTEM: Team organization
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: The imbalance in staffing between optical system (6) and mechanical system (8), and electrical/controls system (2) is troublesome. I understand that project management is aware of this disparity and is implementing corrective action.

RESPONSE: Agreed. We have had some delay in pinpointing the appropriate people to do the electrical control software development. A team is presently formed, comprised of several people from the GSFC Electrical Engineering Division to handle the overall control system architecture and software development, GUI development, electrical I&T, etcetera, and JPL personnel under the direction of Dave Redding to develop the wavefront sensing and control software. We agree that this is an area that needs to be hit hard. The present team has done a great amount of work in the last few weeks and we now have a pretty good handle on the overall control architecture. The interfaces between the overall control system, the wavefront control modules, and the device controllers are presently being defined. (C. LeBoeuf)

43. SUBSYSTEM: Schedule and planning
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: The schedule for completion of Phase I is very aggressive. Experience with astronomical adaptive optics systems (Palomar, Keck, MMT) demonstrates that complexity of optoelectromechanical interfacing within AO systems particularly impacts integration time. Although DCATT is not intended to be either a user facility nor operate in the mountaintop environment, I believe the timeline presented in the presentation underestimates integration time by assuming a number of interdependent activities can proceed entirely in parallel. For example, software developers will require certain optomechanical hardware for prototyping and testing.

RESPONSE: Yes, we realize the schedule we are pushing for is challenging. We have tried to design/procure/develop certain hardware early in order to characterize it so that it can be modeled and control software developed for it. For instance, we already have 6 of the segment actuators/electronics and are building a segment drive mechanism (hexapod arrangement of actuators and flexures). A test program is ongoing to characterize the actuators and it will be extended to characterize the segment level mechanism. The NGST project needs the information from DCATT to assist in decision making in pre and early phase A. The DCATT team will continue to push the schedule and deliver an operational system as soon as is possible. (C. LeBoeuf)

44. SUBSYSTEM: DCATT requirements
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: Although the requirements definition is, by the included timeline, complete, requirements remain unquantified, such as "vibration isolated structure" instead of specifying a tolerance based upon the wavefront knowledge requirement or sensing technique.

RESPONSE: Requirements for the testbed have been developed to the best of our ability at this time through the use of top down error budgets. Our overall philosophy in the design and procurement of hardware for the testbed is to get the best, most precise hardware we can within our budget and schedule. Our error budget is continually updated with estimated hardware data as it is chosen and this will flow into a bottom up error budget. This is only the beginning of our test program. There will be future opportunities to upgrade elements of the system if necessary. (C. LeBoeuf)

45. SUBSYSTEM: DCATT requirements
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: What documentation requirements exist? The scope of this project appears to be within what I consider that dangerous regime where it is too small for formal requirements and interface documentation, but too large to ensure all participants continue to enjoy current information. This usually results in an underestimation of the scope of the project management task.

RESPONSE: Good input. As you say there are no formal documentation requirements. However, we are presently formulating our own interface and requirements documents for the segmented telescope fabrication, the hardware which JPL will be building (Stimulus, Wavefront Sensor, and Interferometric Wavefront Sensor), and for the control software interfaces. (C. LeBoeuf)

46. SUBSYSTEM: Optical design
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL
- SPECIFIC REQUEST: Microroughness of the OAPs is defined without a corresponding spatial scale. The DM can only correct the wavefront on scales commensurate with the actuator spacing.
- RESPONSE: We agree that the limiting factor on the system will probably be the DM. There will be approximately 5 DM actuators across each primary mirror segment, limiting the frequency of error that can be corrected for.
47. SUBSYSTEM: Optical design
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL
- SPECIFIC REQUEST: No stability requirement is presented for the optical mounts. Again, this is important in the context of the accuracy of the wavefront measurement desired. Vibrational, thermal, and possibly flexural motions may all corrupt high-accuracy measurements.
- RESPONSE: This is an issue we will have to work as we begin characterizing the elements of the testbed, flowing the data into the error budget, and integrating the system.
48. SUBSYSTEM: Optical design
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL
- SPECIFIC REQUEST: The CCD Camera Data Transfer Speed should be specified in terms of the data rate per channel, typicallys Mbs. Does the computing architecture support reasonable data transfer times? How frequently will these images be captured?
- RESPONSE: I think I am the only one who specified CCD speeds, and I did it in kHz (as the camera manufacturers do). This implies frame rates to someone in the adaptive optics community; I plead guilty. In the future I will specify it in megabytes (or better, megapixels) per second. (A. Lowman)
49. SUBSYSTEM: Optical design
SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL
- SPECIFIC REQUEST: The Xinetics DM is known to have temperature dependent hysteresis (see the WWW page for Keck AO - however recently Ealey has improved his process). Is this a concern for DCATT?
- RESPONSE: Firstly, the DM procurement which we just released is open for bids by companies other than Xinetics and we will select the one which best fulfills the DCATT requirements. As far as temperature dependence in general, the lab environment is fairly stable. We measured a maximum change of $\pm 2^{\circ}\text{F}$ over about four weeks this Fall during which time the outside temperature was fluctuating quite a lot. It typically stayed within $\pm 1^{\circ}\text{F}$ over a several day period. Whether or not this level of fluctuation will knock us out of our envelope of control is presently unknown, but part of the testbed function is to determine how robust the overall control system is. Stability over time is one of the parameters that will be investigated. The DM will be fully characterized prior to integration with the system, including stability over a several day time period. (C. LeBoeuf)

50. SUBSYSTEM: Optical error budget

SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: From the description of the optical layout, there is on the order of 30 meters of optical path in the testbed. The allocation of $\lambda/40$ wavefront error for lab seeing is probably not sufficient. The Palomar AO system has demonstrated > 60 nm rms (spatial) wavefront error due to lab seeing over ~ 20 meter path, when enclosed (the Palomar enclosure does possess several 4" cabling ports). This turbulence develops on time scales of seconds. If additional effort is taken to minimize lab seeing (use of input windows, etc.) this should be noted and accounted for elsewhere in the design.

RESPONSE: The testbed layout and design of the Stimulus have been changed such that the path length has been much reduced, though it is still fairly long. Basically, the source light used to be double passed through both the telescope and the AO bench. Now it is only double passed through the telescope. There are also plans to build an enclosure of some sort around the testbed. This has not been designed yet. (C. LeBoeuf)

51. SUBSYSTEM: Control/Electrical subsystem

SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: The level of detail devoted to the electronics, controls, and, particularly, the software for DCATT is not commensurate with the detail performed on the optical and mechanical designs.

RESPONSE: This area is presently being worked. (C. LeBoeuf)

52. SUBSYSTEM: General comments

SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: The DCATT team has made rapid progress in the definition of the Phase I DCATT testbed, particularly in the optomechanical and structural design. Several important subsystems still require better definition, most importantly the electronics and software design. Control software and the operational scenarios of performing NGST technology demonstrations require detailed consideration.

RESPONSE: This area is presently being worked. (C. LeBoeuf)

53. SUBSYSTEM: General comments

SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: The remaining Phase I schedule is very aggressive. To meet the desired schedule, long-lead procurements must be made prior to the completion of the detailed design. This raises the risk that mistakes will be made, and this should be considered in the project resource planning.

RESPONSE: To the extent that DCATT has control over available resources, this is being done. (C. LeBoeuf)

54. SUBSYSTEM: General comments

SOURCE: Dr. Richard Dekany, Interferometer Systems Group, JPL

SPECIFIC REQUEST: Most, if not all, astronomical adaptive optics projects have underestimated the scope of the software task. Although DCATT does not suffer the same high bandwidth requirements as ground-based AO, it does possess similar optoelectromechanical complexity. Proper software design, including robust motion control, digital I/O, D/A, and A/D modules, is critical to satisfying the goals of the testbed. The various DCATT computing platforms increasing the interface complexity and adds risk to an integration schedule already stressed.

RESPONSE: This area is presently being worked. (C. LeBoeuf)

NGST Technologies & Validation Facilities, Testbeds and Flight Demonstrations

	Primary Mirror Optical Test Facility	Dynamics Test Facility	Cryogenic Actuator Tested Facility	DCATT Tested/Cryo Test Chamber	Industry Deployment Testbeds	AF Phillips Lab ULTRALITE Tested	Space Interferometry Mission Testbeds	Infrared Array Test Facilities	Cryocooler Test Facilities	Science Instrument Tested	Observatory Test Facilities	Inflatable Sunshade Ground Demo	Ground/Flight Operations Tested/Sim.	HPCC Program Tested	Flight System Tested	Pathfinder 1 Flight Demo	Pathfinder 3 Flight Demo	Integrated NGST Models
Lightweight Cryogenic Primary Mirror	X	X													X		X	X
Cryogenic Actuators	X		X	X											X		X	X
Cryogenic Deformable Mirror				X													X	X
Wavefront Sensing/Control & Fine Guidance/Pointing Methodology				X									X	X	X		X	X
Precision Deployable Structures		X			X	X									X		X	X
Vibration Control					X	X	X										X	X
Large Format, Low Noise IR Arrays								X		X	X						X	
Vibrationless, Long Life Cryocoolers									X	X	X						X	
Lightweight Inflatable Sunshade												X				X		X
Advanced On-Board and Ground Operations Methodology													X	X		X	X	
Advanced Telescope Systems			X												X		X	X